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HYDRAULIC MODEL STUDY OF RITSCHARD DAM SPILLWAYS

October 1991

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16. ABSTRACT

The Bureau of Reclamation conducted a physical model investigation to help design the hydraulic structures associated with Ritschard Dam. Ritschard Dam will have a labyrinth weir emergency spillway and an uncontrolled ogee crest service spillway, both of which are expected to convey flows beyond the limits of contemporary design criteria. Preliminary flume studies were conducted on sections of the labyrinth and ogee crests to determine discharge coefficients and surface pressure distributions (ogee only). The Ritschard Dam model was used to determine if the ogee and labyrinth spillways could, in combination, convey the probable maximum flood peak outflow. In addition, the model was used to determine the most efficient energy dissipation structure for the service spillway and flow conditions in Muddy Creek.

17. KEY WORDS AND DOCUMENT ANALYSIS

a. *DESCRIPTORS*-- hydraulic model study\ labyrinth weir\ ogee crest\ discharge coefficient\ stepped spillway chute\ energy dissipation

b. *IDENTIFIERS*-- Ritschard Dam\ Wolford Mountain Project\ Colorado River Water Conservation District\ Muddy Creek\ Kremmling, Colorado\ high-capacity ogee\ supersaturation\ emergency spillway

c. *COSATI Field/Group* *COWRR:* *SRIM:*

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UNITED STATES DEPARTMENT OF THE INTERIOR ★ BUREAU OF RECLAMATION

PURPOSE

Reclamation engineers conducted a model study at the Denver Office Hydraulics Laboratory to determine if the morning-glory spillway at Beaver Run Dam, Pennsylvania, would operate safely using revised flood hydrology. The Pennsylvania Department of Environmental Resources, Division of Dam Safety, requested Reclamation's assistance based on hydraulic laboratory experience in conducting investigations of morning-glory spillways. Beaver Run Dam is owned and operated by the Municipal Authority of Westmoreland County. Should performance of the present spillway warrant improvement, structural modifications to the morning-glory spillway will be developed to attain acceptable hydraulic performance from the structure.

CONCLUSIONS

1. Performance of the existing spillway is not acceptable for the increased reservoir elevations associated with the revised PMF (probable maximum flood). At a reservoir elevation of 1054.6 ft ($Q = 3{,}650$ ft^3/s), the pipe becomes pressurized or flows full.

2. A flow deflector and an air vent are required to reduce the spillway capacity and to maintain uniform open-channel flow throughout the tunnel conduit. Discharge with the recommended flow deflector and air vent is limited to 2,500 ft^3/s at elevation 1070 ft.

3. Pressure measurements for the recommended design indicated that the potential for cavitation development and cavitation erosion is minimal.

4. Hydraulic performance of the outlet structure changes due to increased velocities in the tunnel conduit associated with the spillway modifications. Likewise, increased wave action may cause riprap instability downstream of the outlet structure.

APPLICATION

Application of the specific conclusions from these studies is limited to structures and hydraulic flow conditions similar to those tested. The discharge relationship, flow deflector size, air demand, conduit flow conditions, and surface pressures are functions of the approaching flow patterns, structural arrangement, and tailwater conditions. Applying the results of this study to another structure would be difficult unless the preceding factors were completely similar.

INTRODUCTION

Beaver Run Dam is located in west-central Pennsylvania on Beaver Run in Westmoreland County. Perrysville and North Washington are neighboring communities. This dam and reservoir provide water for municipal and industrial use.

Beaver Run Dam, completed in 1952, is an earthfill structure approximately 1,095 ft long and 91 ft above the streambed. Principal features include a 10-ft-diameter morning-glory spillway, two 42-in-diameter cast iron tunnel conduits, and an emergency spillway located in the left abutment. The reservoir provides storage of 34,000 acre-ft before discharging through the morning-glory spillway (crest elevation of 1050.1 ft), and 74,000 acre-ft at a maximum reservoir elevation of 1075.0 ft.

The morning-glory spillway is located near the left abutment of Beaver Run Dam. The only major modification to the dam was in 1962 when the crest elevation was raised from 1045 to 1050.1 ft. The modified spillway is 37 ft in diameter at the crest and has twelve 1-ft-wide piers, four of which are walkway supports. The shaft below the drop inlet is vertical for a distance of 45 ft and tapers to a diameter of 10 ft. At elevation 1004.5 ft, a vertical bend changes the flow direction 90° into a concrete-lined tunnel. The 320-ft-long tunnel has a slope of 0.005. Total drop from the crest to the tunnel portal invert is 67.2 ft. A reinforced concrete outlet structure and 200-ft-long rock-lined channel are used to dissipate excess energy in the flow before releasing the water into the natural river channel.

The primary objectives of this study were to:

1. Construct a hydraulic model to determine the hydraulic effects of the revised PMF on the existing morning-glory spillway structure.

2. Determine if the spillway is susceptible to vibrations caused by make-and-break siphonic action which occurs when flow in the spillway conduit fluctuates between open and closed conduit flow.

3. Develop backwater rating curves for Beaver Run downstream of the dam using channel cross section data provided by the Westmoreland County Authority.

4. Collect average piezometric pressure data on the spillway crest inlet, and along the invert of the transition section, vertical bend, and tunnel conduit.

5. Determine a discharge rating for the existing spillway for a 25-ft range of reservoir elevations up to a maximum elevation of 1075 ft.

6. Investigate up to three alternatives for modifying the spillway structure to yield satisfactory hydraulic conditions. Develop a discharge rating relationship for the recommended spillway modifications.

THE MODEL

The hydraulic model was constructed to a 1:21.81 scale because it allowed the use of 5.50-in i.d. (inside-diameter) clear acrylic pipe to simulate the 10-ft i.d. spillway tunnel. Five and one-half inch acrylic pipe is commercially available; therefore, it reduced the time and effort required to construct the model.

The model included:

- **Head box with reservoir topography.** - A gravel-filled baffle was included on three sides of the 16- by 16-ft head box to smooth the water surface and evenly distribute the inflow. Topography included a portion of the upstream face of the dam from an elevation of 990 ft to the crest of the dam at 1,075 ft. There was adequate topography in the model to accurately simulate approach flow conditions towards the crest. Other major features in the surrounding area were also modeled (figs. 1 and 2).

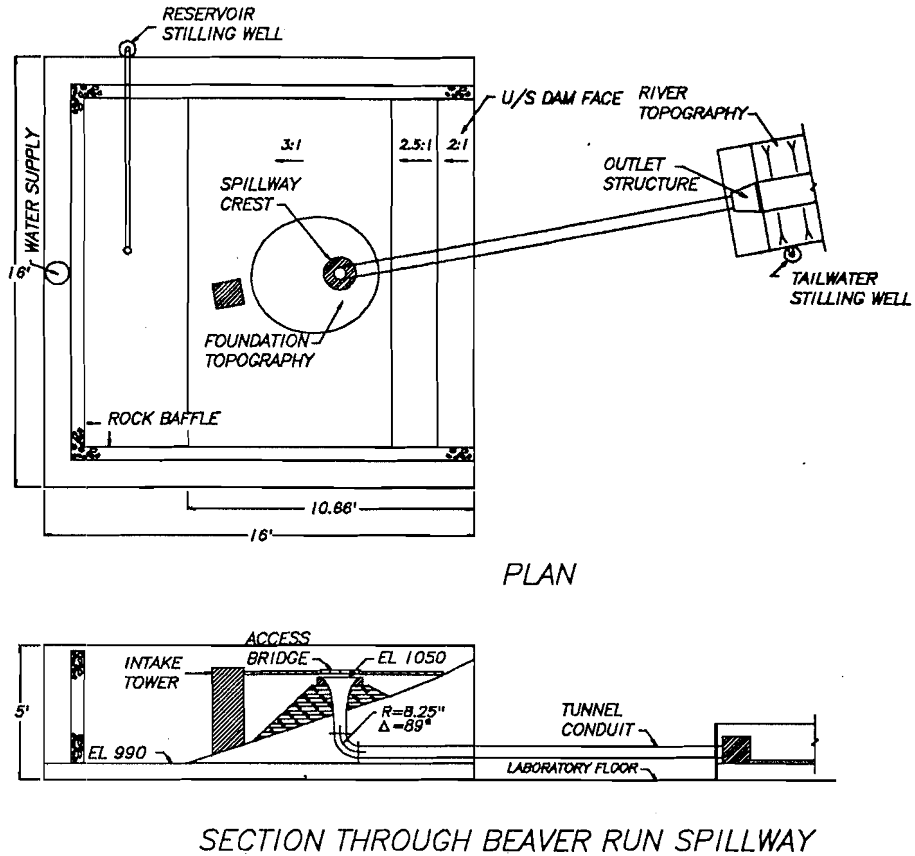

Figure 1. - Model layout (scale 1:21.81).

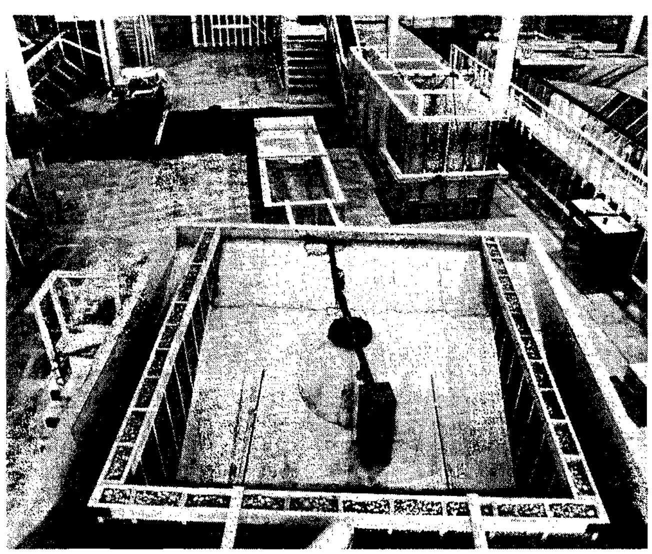

Figure 2. - Overview of model head box and tailwater box and their appurtenances.

- **Crest inlet and piers.** - The crest inlet and piers were constructed of high-density urethane. Two rows of piezometers were installed to measure surface pressures on the crest. The piezometers were centered between two adjacent piers to monitor the hydraulic conditions in the area of concentrated flow. A total of 29 piezometer taps were used to measure the pressure head on the flow surfaces. Two rows of six taps each were placed on the crest inlet; the rows were 90° apart (fig. 3).

- **Spillway features below crest inlet.** - Spillway sections below the crest inlet were modeled using clear acrylic plastic. The transition, vertical bend, and circular conduit sections were fabricated in Reclamation's laboratory shops (fig. 4). Fourteen piezometer taps were placed along the invert of the transition, vertical bend, and tunnel. Three taps were mounted on the crown of the tunnel just downstream of the vertical bend. The locations of the pressure taps and their identification numbers are shown on figure 3.

- **Outlet structure with downstream topography.** - The 8- by 4-ft tail box included the outlet structure and 200 ft of channel topography up to an elevation of 995 ft (fig. 1). An adjustable tailwater gate was installed to control tailwater elevations. The two 42-in outlet pipes were not incorporated into the model.

- **Data collection.** - Model flow rates were measured using venturi flowmeters. Water surface elevations in the headwater and tailwater boxes were determined using hook-type point gauges, mounted in clear plastic stilling wells. Average piezometric pressures were measured using a pressure transducer and an integrating voltmeter.

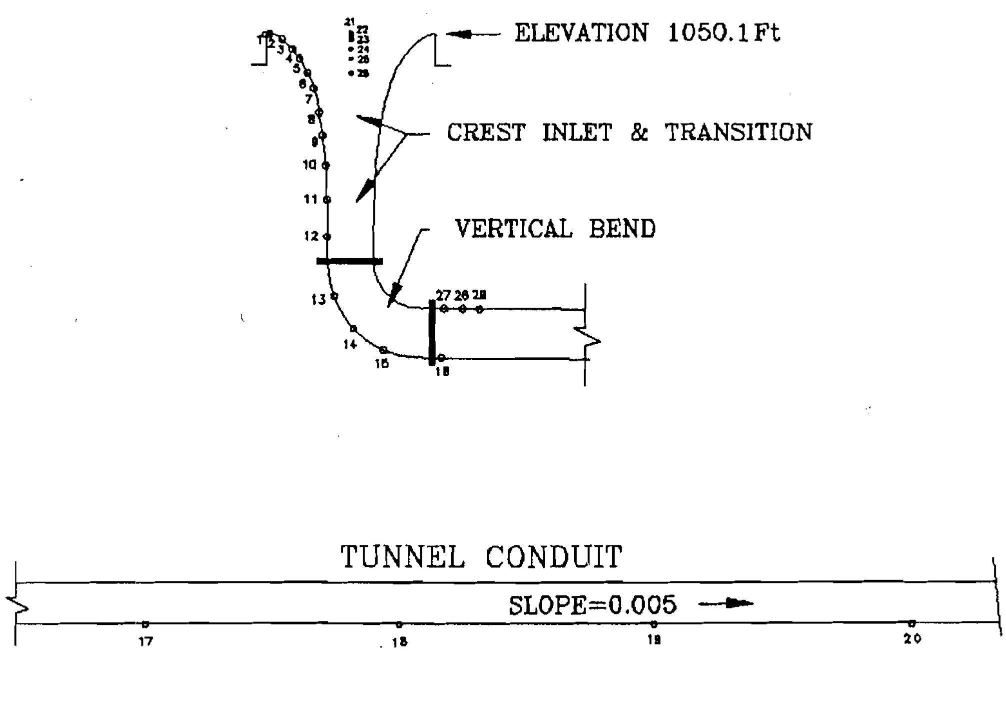

Figure 3. - Piezometer tap locations.

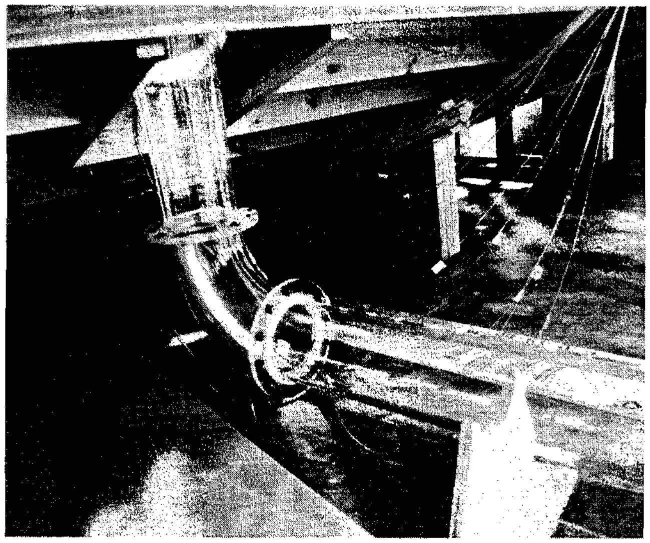

Figure 4. - View of transition, vertical bend, and circular conduit sections.

THE INVESTIGATION

Hydraulic conditions in the spillway inlet, vertical shaft, vertical bend, and outlet tunnel were investigated for reservoir levels up to the maximum water surface elevation of 1075 ft. The primary objective was to determine if the outlet tunnel would seal and become pressurized during a flood event. If conditions warrant, spillway modifications will be developed to provide acceptable performance.

Tailwater Elevations

In order to accurately model flow through the morning-glory spillway, a relationship between the spillway discharge and the tailwater elevation was developed using the U.S. Army Corps of Engineers' water surface profile computer model, HEC-2. Backwater profiles were developed under the premise that the only flow into Beaver Run was discharging through the spillway. Channel, highway bridge, and flood plain cross-section data were provided by the Municipal Authority of Westmoreland County. Figure 5 shows the tailwater rating curve for channel station 3+64, located 40 ft downstream from the tunnel portal.

Flow Distribution

The flow distribution within the head box was examined to verify that the flow entering the spillway was representative of the prototype reservoir. Flow conditions into the spillway and vortex development are a function of the distribution and direction of the approaching flow. Because water is pumped into the head box through a 12-in-diameter steel pipe, a gravel-filled baffle was necessary to distribute the inflow evenly and dampen the surface waves. The approaching flows were examined using confetti to create streaklines (fig. 6). Approaching flows were smooth and irrotational over the complete range of discharges.

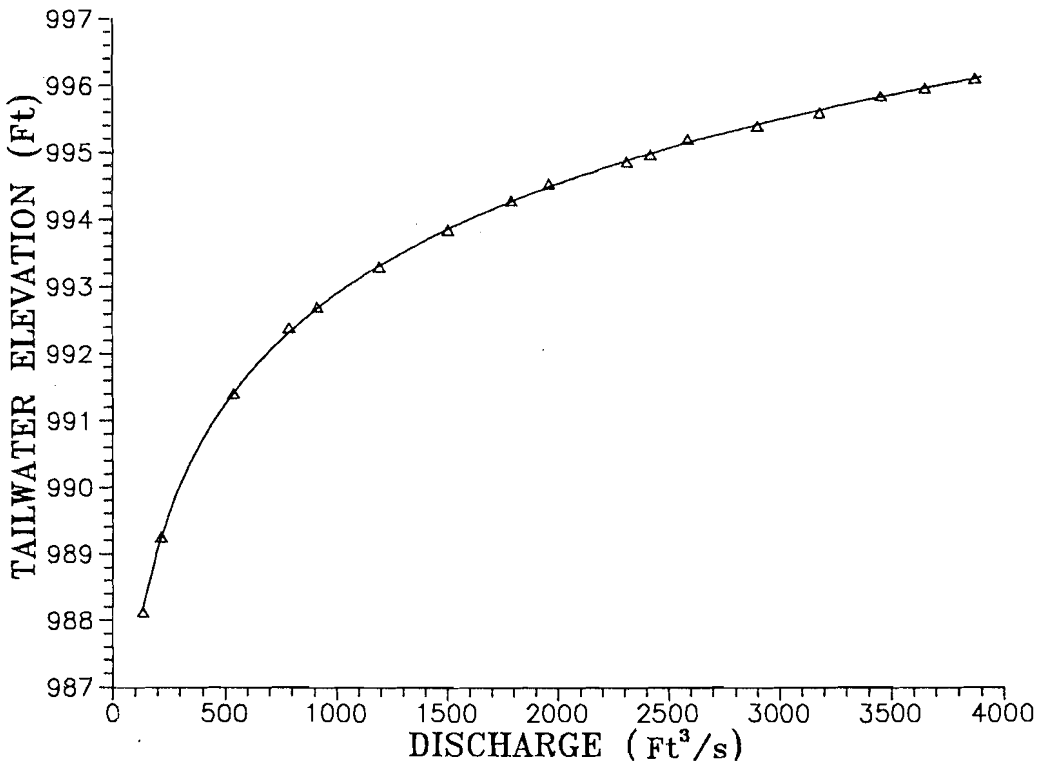

Figure 5. - Tailwater rating curve (Sta. 3+64).

Figure 6. - Typical approaching flow pattern.

The Crest

The existing crest and pier configuration provides adequate vortex control; that is, there is no significant vortex formation at low flows. At higher reservoir levels the crest inlet becomes submerged, and some vortex activity was observed. However, these vortices are weak and are dissipated by the influence of the intake tower walkway.

Flow characteristics in the approach and inlet. - The flow approaches the crest inlet satisfactorily. As flow plunges over the crest, it is evenly distributed between the piers. This provides uniform flow into the vertical shaft and transition sections, as well as air entrainment into the flow. The crest inlet is ungated; therefore, it is an uncontrolled outlet and the discharge cannot be regulated. At low heads the discharge through the spillway is controlled by weir flow over the crest. At higher heads, the water surface begins to rise in the vertical shaft and eventually submerges the crest. When this occurs the spillway discharge is controlled by orifice flow within the vertical shaft. The transition causes a significant change in slope of the discharge rating curve (fig. 7). The data do not indicate the exact water surface elevation where this change occurs because there is a range of discharges where the control location fluctuates between weir and throat control. At a discharge of 3,650 ft^3/s, the inlet begins to submerge; this is indicated by a boiling water surface in the inlet. For water surface elevations in excess of approximately 1,055 ft, the spillway crest is completely submerged and the throat section controls discharge through the spillway. Under submerged flow conditions, air entrainment is virtually eliminated.

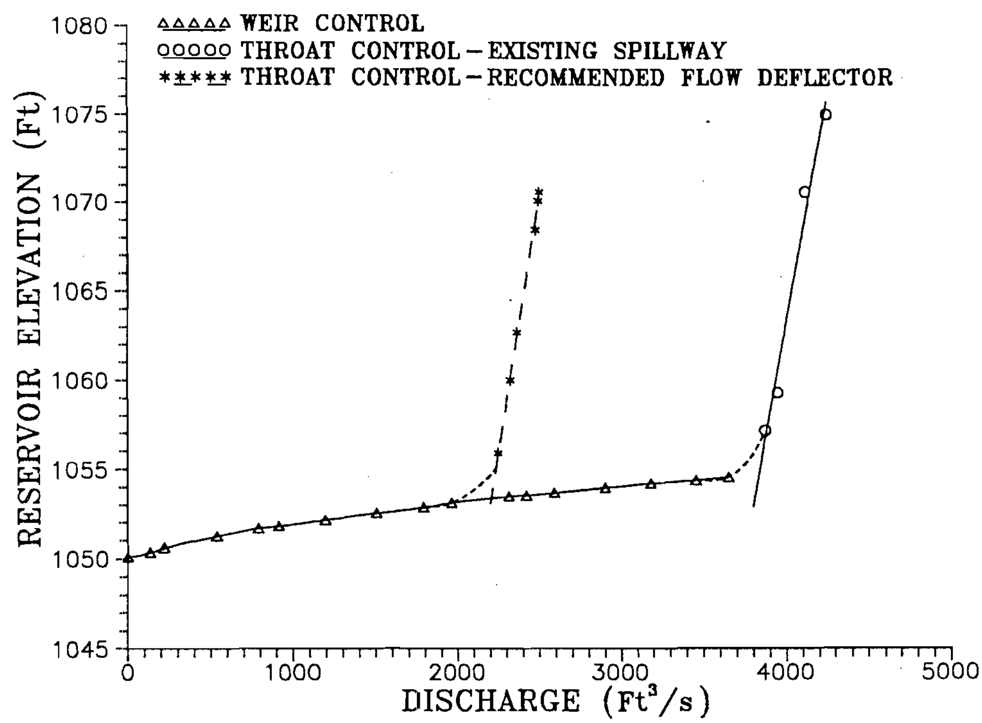

Figure 7. - Morning-glory spillway rating curve.

Flow characteristics in the tunnel conduit. - Flow conditions through the conduit were observed for discharges in the range of 200 to 4,240 ft^3/s. In general, the water surface and flow conditions in the vertical shaft, vertical bend, and tunnel are very uniform and stable. At low discharges flow concentrates, forming a fin in the center of the conduit downstream of the elbow. This causes intermittent splashing on the conduit crown. For intermediate flows the finning decreases and the water surface is stable throughout the tunnel length. For discharges in the range of 2,600 to 3,000 ft^3/s, the tunnel conduit flows about 90 percent full for its entire length. For these discharges there is minor surging as flow passes between open and closed conduit flow. This situation is undesirable because of the dynamic forces it applies to the tunnel lining. Reclamation's recommended design practices for morning-glory spillways specify that the tunnel conduit should not flow more than 75 percent full (Bureau of Reclamation, 1987). This criterion protects the conduit from surging flows or flowing under pressurized conditions. For discharges greater than 3,650 ft^3/s, the tunnel is pressurized for its entire length.

Flow surface pressures. - Three groups of piezometer taps were used to measure the spillway and conduit surface pressures. Taps numbered 1 through 20 were installed down the invert of the tunnel and along the centerline of the spillway structure. Flow over taps 1 through 6 was obstructed by the intake tower bridge; therefore, taps 21 through 26 were installed 90° counterclockwise from taps 1 through 6 (fig. 3). For all discharges, pressures on the crest inlet are near or above atmospheric and do not represent a cavitation potential. The largest pressures occur in the vertical bend because of the centrifugal forces associated with curvilinear flow. The maximum pressure was observed at tap 15, where a pressure of 60 ft of water was measured for a discharge of 4,240 ft^3/s. Maximum pressures measured along the invert of the tunnel conduit were in the range of 37 to 15 ft of water from tap 16 to tap 20, respectively, at 4,240 ft^3/s. This indicated that the 10-ft-diameter tunnel conduit was pressurized throughout its length. Figure 8 shows the pressure profiles, plotted vertically, for discharges equal to 2,675 and 4,240 ft^3/s. Note that pressure values for taps 1 through 6 and 21 through 26 plotted on top of one another and are only slightly different in magnitude. Additional pressure data for the existing spillway are tabulated in the appendix, tables A.1 to A.7.

Stage-discharge relationship for existing conditions. - For the existing spillway configuration, a stage-discharge relationship was developed over the range of operational reservoir elevations – 1050.1 to 1075 ft. Results of this test were:

1. A maximum discharge of 4,240.0 ft^3/s is passed at a reservoir elevation of 1075.0 ft. The morning-glory inlet is completely submerged and the spillway tunnel is pressurized over its entire length. Note that tailwater elevations could not be computed for reservoir water surface elevations over 1070 ft because there is insufficient information on the inflow into Beaver Run from the emergency spillway.

2. The tunnel conduit flows 75 percent full at the outlet for a discharge equal to 2,300 ft^3/s (reservoir elevation 1053.5 ft).

3. Surging occurs as the conduit flow alternates between open and closed conduit flow for a discharge of 2,675 ft^3/s.

4. Inlet submergence starts at a flow rate of 3,650 ft^3/s. Discharge control shifts from weir flow to orifice flow at an approximate discharge of 3,900 ft^3/s.

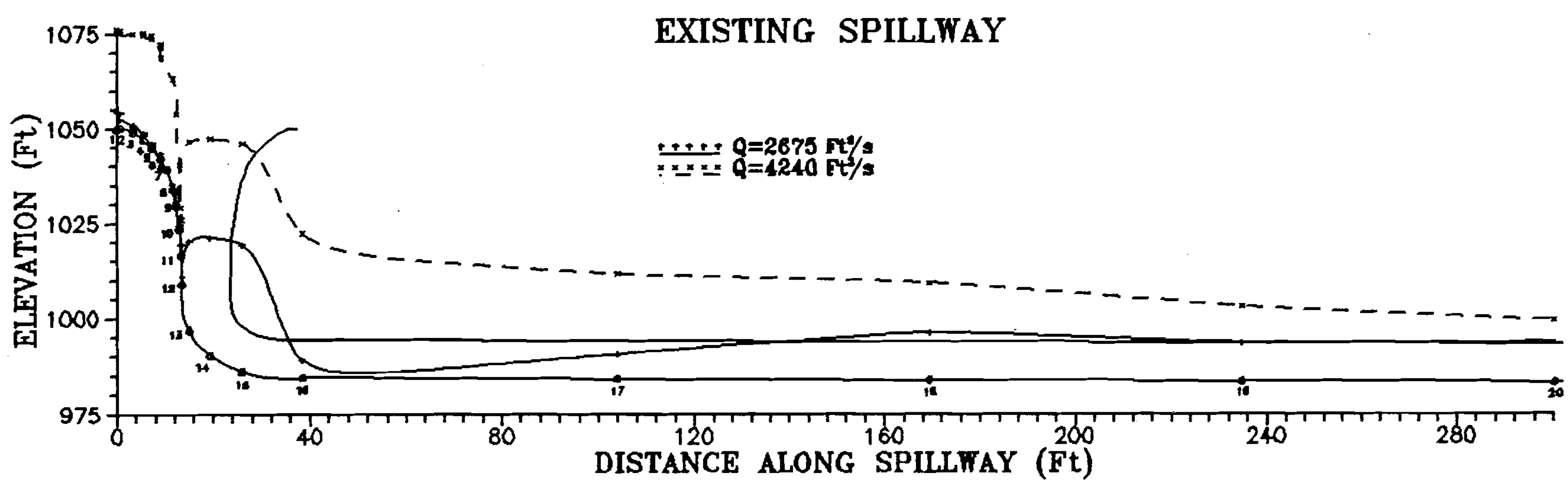

Figure 8. - Pressure profiles for existing spillway.

From these results it is apparent that the morning-glory spillway, in its existing condition, does not operate satisfactorily for reservoir elevations greater than 1053.5 ft. As a result, modifications to the morning-glory spillway are required to ensure its safe operation up to the maximum reservoir elevation of 1075 ft.

Preliminary Vertical Bend Modifications (Flow Deflector 1)

In order to prevent the spillway conduit from flowing full, it is necessary to constrict the throat section using a flow deflector. This technique has been used on other morning-glory spillways with success. The flow deflector guides the flow toward the invert of the vertical bend and tunnel. The flow deflector was designed to limit the discharge to 2,300 ft^3/s and prevent the tunnel conduit from flowing more than 75 percent full at the maximum reservoir level. The reduction in flow area was calculated using the orifice flow equation with a coefficient of discharge equal to 0.9.

The flow deflector, fabricated from high-density urethane, was installed at the point of curvature of the vertical bend and extended vertically downward 11.5 ft, then horizontally 10.6 ft [fig. 9(A)]. Two piezometers (27A and 28A) were mounted on the vertical and horizontal faces of the flow deflector to measure surface pressures. The flow deflector reduced the cross-sectional area of the 10-ft-diameter vertical bend by 52.3 percent, which resulted in a 37-ft^2 open area.

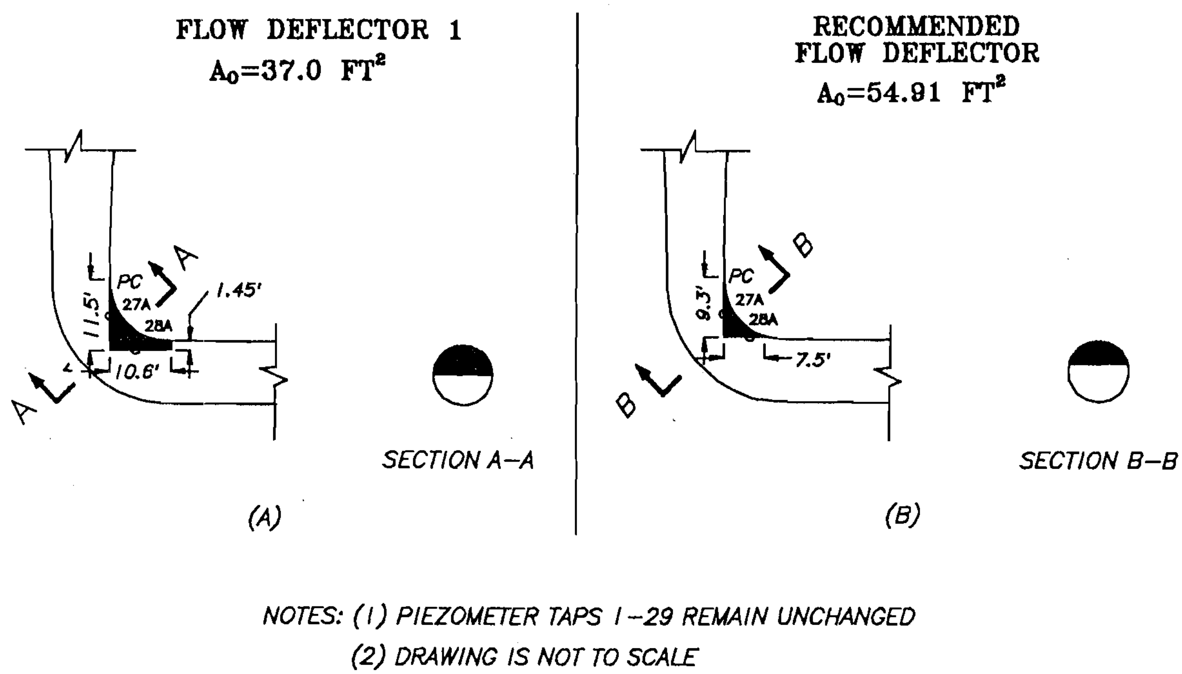

Figure 9. - Flow deflector designs.

The flow deflector provided a smooth flow profile through the bend and into the tunnel over the complete range of discharges. However, head-discharge measurements showed that the flow deflector was oversized, thereby reducing the capacity of the spillway to 1,385 ft^3/s, well below the design value of 2,300 ft^3/s. In addition, as the tailwater elevation increased with discharges larger than 1,340 ft^3/s, a hydraulic jump migrated from the outlet structure into the conduit. The hydraulic jump intermittently closed off the downstream air supply into the conduit. This caused an increase in the subatmospheric pressure in the tunnel, an increase in net head across the flow deflector, and thus a sudden increase in the discharge. The higher discharge washed the hydraulic jump out of the conduit and reestablished free surface flow. This cyclic phenomenon resulted in a surging flow pattern which featured large pressure fluctuations (±45 ft of water) within the conduit and excessive wave action in the downstream channel (fig. 10).

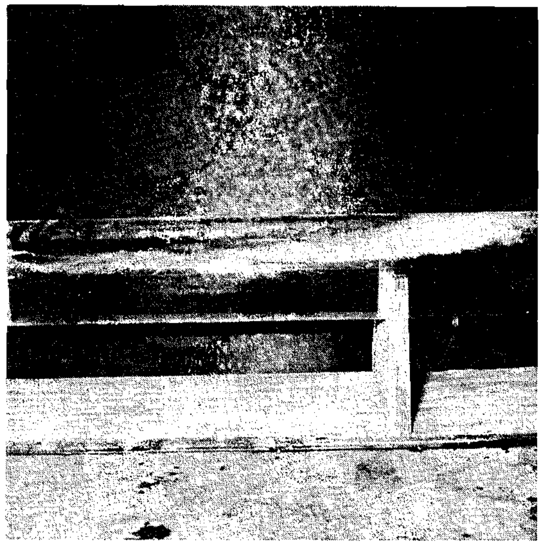

Figure 10. - Surging flow from left to right.

The following results from the initial flow deflector design were used to guide the final testing program:

1. Shape and location of the flow deflector created smooth and stable flow patterns within the tunnel conduit. This was true for hydraulic control in both weir and orifice flow regimes.

2. The flow deflector would have to be modified so that it could pass at least 2,300 ft^3/s. The flow deflector size would be revised based on the coefficient of discharge calculated using head-discharge data from the initial flow deflector tests.

3. An air vent is necessary to relieve subatmospheric pressures in the conduit in the event that the tailwater submerges the tunnel outlet during spillway operations. Venting the tunnel conduit will eliminate surging and maintain open-channel flow throughout the tunnel conduit.

4. Determine the air flow rate required to maintain free-flow conditions. This quantity must be known to design the air supply conduit.

Recommended Vertical Bend Modifications (Flow Deflector 2)

In order to pass the design discharge, the flow deflector was modified based on a revised coefficient of discharge equal to 0.6. The flow deflector was reinstalled beginning at the point of curvature of the vertical bend and extended vertically downward 9.3 ft, then horizontally 7.5 ft. The modified flow deflector reduced the cross-sectional area of the 10-ft-diameter conduit by 30.1 percent for an open area of 54.9 ft^2 [fig. 9(B)]. Piezometer taps 27A and 28A remained in the same positions, except tap 28A was adjusted to the proper elevation.

The modified flow deflector produced flow patterns similar to the results stated for the preceding design. The inlet submerged at a discharge of 2,200 ft^3/s. For a reservoir elevation of 1070 ft, the discharge through the morning-glory spillway was 2,500 ft^3/s, and the conduit flowed approximately 50 percent full. Therefore, this flow deflector meets both design parameters: (1) discharge should be at least 2,300 ft^3/s, and (2) the conduit should be less than 75 percent full. It should be noted that tailwater conditions for reservoir water surface elevations over 1070 ft could not be accurately predicted because of unknown inflows from the emergency spillway. Consequently, spillway performance for reservoir elevations above 1070 ft can only be approximated. However, the flow deflector performed satisfactorily for a discharge of 2,300 ft^3/s and for 15 ft of additional tailwater (tailwater elevation = 1010 ft).

Air Vent

Observations of the spillway show there are two natural sources of air flow into the tunnel conduit. First, venting occurs as air is entrained by water passing over the crest. This entrainment is greatly reduced as the crest submerges. Second, maintaining open-channel flow within the tunnel allows air to enter above the water surface at the downstream portal. Venting occurs as long as the tailwater elevation does not rise sufficiently to seal the tunnel portal. If this occurs as previously discussed, pressure within the conduit lessens prompting the hydraulic jump to move into the conduit, and surging flow develops.

To ensure that the conduit is always vented to the atmosphere, an air vent is needed. In the model, an air vent was installed on the crown of the tunnel conduit just downstream of the vertical bend. It consisted of a pipe mounted flush to the conduit crown capped by an orifice plate (fig. 11). To determine the size of air vent needed to prevent surging, tests were conducted with several different sizes of orifice plates mounted over the model vent pipe. Air flow rates were determined by measuring the pressure differential across the orifice. Maximum air demand was determined by maintaining 2,300 ft^3/s through the spillway and measuring the air flow rates for an extended range of tailwater elevations. It was important to determine the air demand for higher tailwater levels to test for surging flow conditions. The maximum average and instantaneous air demands measured were 125 and 150 ft^3/s, respectively. Figure 12 shows the average air demand versus tailwater elevation for 0.5-ft (0.25-in model) and 0.7-ft (0.375-in model) diameter air vent orifices for the design discharge of 2,300 ft^3/s. Surging flow conditions were observed for the 0.5-in-diameter orifice vent at a tailwater elevation of 996.6 ft. This indicated that a larger air vent was required. By increasing the size to a 0.7-in-diameter orifice, the spillway operated satisfactorily for all tailwater levels tested. The prototype air vent must be designed to provide equal or less head loss than generated by the simulated vent (orifice) in the model.

Air vent design. - The air vent for the prototype can be designed from the model results based on the equation (Falvey, 1980):

$$A_v = A_o C_d L_r^2 (1 + \sum K_s + \frac{fL}{4R})^{1/2} \qquad (1)$$

where

A_v = area of Prototype air vent (ft^2)

A_o = area of model orifice (0.00077 ft^2)
C_d = coefficient of discharge for model orifice (0.6)
L_r = prototype to model scale ratio (21.81)
$\sum K_s$ = summation of coefficients for singular losses (entrance, bends, and changes in area)
f = Darcy-Weisbach friction factor for the prototype air vent
L = length of prototype air vent (ft)
R = hydraulic radius of the prototype air vent (ft)

By substituting constants into equation (1), the prototype air vent can then be designed using:

$$A_v = 0.2198(1+\sum K_s + \frac{fL}{4R})^{1/2} \tag{2}$$

For the prototype, the air vent conduit could be installed along the crown of the tunnel from the flow deflector to the portal, and then brought back up the downstream dam face to reach above maximum tailwater elevation. Near the tunnel portal, such a vent should be designed to withstand flow impingement as the jump remains very near the portal exit under high tailwater conditions. An alternative design would be to install the conduit through the downstream face of the dam. For either case the air vent conduit should discharge just downstream of the flow deflector.

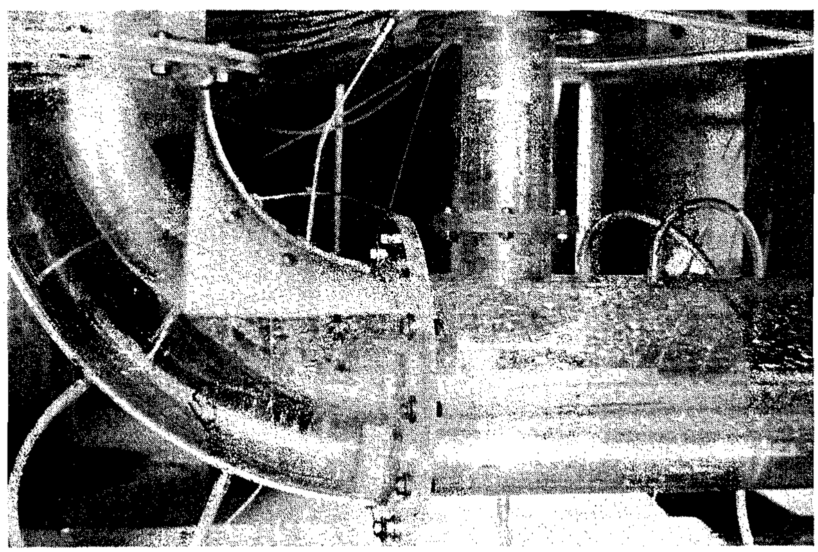

Figure 11. - Air vent with orifice plate (Q = 1,300 ft^3/s).

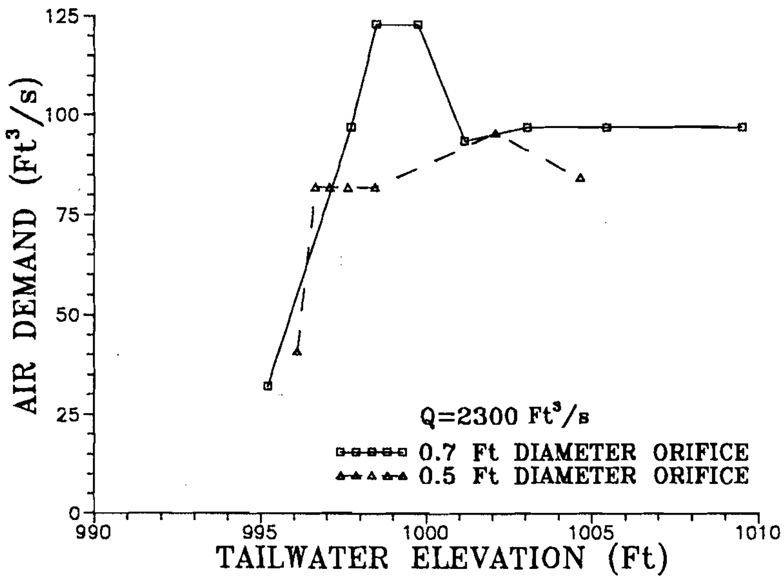

Figure 12. - Air demand curves for recommended flow deflector.

Pressure Profiles

Pressure data were collected for a discharge of 2,323 ft³/s to determine the effect of the flow deflector on the pressure profile along the invert of the spillway. Another piezometer tap was installed to measure the pressure on the crown of the tunnel, downstream from the air vent. A graph of the pressure profiles is shown in figure 13. Pressures within the vertical bend were large, 53 ft of water at piezometer tap 13, because of the centrifugal forces associated with curvilinear flow. Tap 27A has a lower surface pressure (42 ft) because it had a reduced role in redirecting the flow into the tunnel conduit. Piezometers 28A and 29 both indicated near-atmospheric pressure along the crown or free surface flow. Pressure data for all piezometer taps are presented in appendix table A.8. As a result, the potential for cavitation damage is reduced. As a precaution, the cavitation damage potential within the tunnel conduit was analyzed using a computer model. The model calculates flow velocity, water surface profiles, boundary layer development, and potential for cavitation damage. The model does not include the effects of air entrainment in its computations. However, there is very little air entrainment in the morning-glory spillway at higher heads because of inlet submergence. The computer analysis indicated that there is very limited potential for cavitation damage. However, the analysis was based on a relatively smooth flow surface (Manning's n = 0.012). If large surface imperfections exist, such as offsets at construction joints or abraded surfaces, the potential for cavitation increases. It should be noted that there was some confusion as to whether a steel conduit still protrudes into the spillway near the lower portion of the vertical bend. If so, it should be excavated and repaired to provide a smooth transition into the tunnel conduit.

Outlet Structure

Observation of the outlet structure indicated minimal energy dissipation capacity at higher discharges for both the existing and modified spillway configurations. Consequently, flows through the rock-lined channel are rapid and highly turbulent. The modified spillway will increase this problem by improving

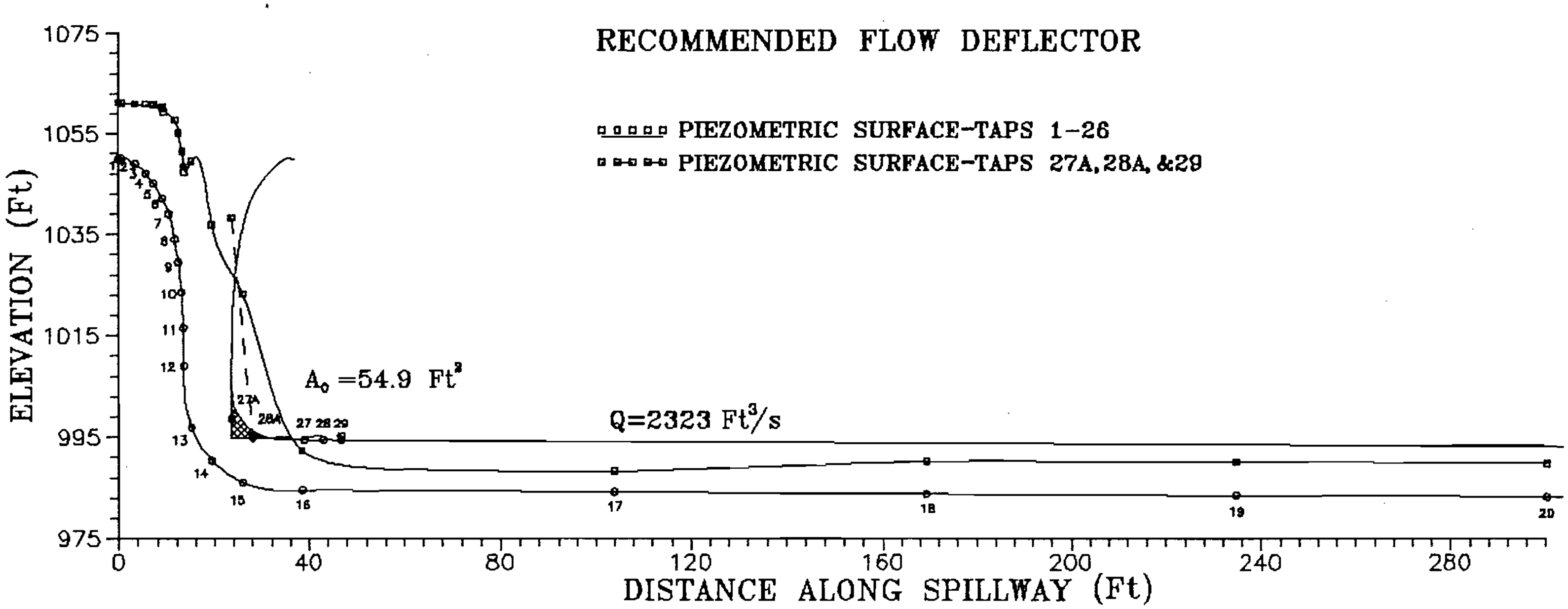

Figure 13. - Pressure profile for recommended flow deflector.

the flow conditions through the spillway, thereby reducing the energy dissipation within the tunnel conduit. At 2,300 ft^3/s through the modified spillway, a noticeable increase in flow velocity and turbulence was observed downstream of the outlet structure. As a result, riprap stability and freeboard will be reduced during high flows. These observations were for a tailwater elevation of 995 ft. It is conceivable that during events which require large reservoir releases the tailwater could be much higher. In this case the effects of the higher velocity flows would be diminished. Flow conditions for high tailwater were not investigated because the channel topography was limited in elevation to 995 ft.

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APPENDIX

Piezometer pressure data for Beaver Run Dam hydraulic model study

Table A.1. - Piezometric pressure data for existing spillway (Q=2675 ft^3/s)

Spillway discharge (ft^3/s) 2675.00	Tailwater El. (ft) 995.71	Reservoir El. (ft) 1053.85	Data filename DRUCK4.ASC	
Tap No.	X coordinate (ft)	Y coordinate (ft)	Piezometric elevation (ft)	Pressure head (ft H_20)
1	0.00	1049.92	1054.49	4.57
2	0.63	1050.10	1054.09	3.99
3	3.41	1049.23	1050.23	1.00
4	5.59	1047.37	1048.32	0.95
5	7.25	1045.36	1046.21	0.86
6	9.08	1042.33	1043.41	1.08
7	9.25	1039.35	1040.15	0.79
8	11.59	1034.56	1035.28	0.72
9	12.34	1030.60	1030.72	0.12
10	13.05	1023.69	1024.60	0.91
11	13.37	1016.73	1019.33	2.61
12	13.50	1009.53	1010.86	1.33
13	15.01	996.27	1020.34	24.07
14	19.32	990.46	1021.29	30.83
15	25.83	986.32	1019.33	33.01
16	38.40	984.80	989.20	4.40
17	103.85	984.70	990.65	5.95
18	169.30	984.30	996.22	11.92
19	234.75	984.08	993.61	9.53
20	300.20	983.79	993.76	9.97
21	0.63	1050.18	1052.28	2.10
22	3.41	1049.42	1050.93	1.51
23	5.59	1047.44	1048.87	1.43
24	7.25	1045.45	1046.26	0.82
25	9.08	1042.20	1041.90	-0.30
26	9.25	1039.20	1039.49	0.29
27	38.95	994.47	n/a	n/a
28	43.00	994.45	n/a	n/a
29	46.76	994.43	n/a	n/a

Table A.2. - Piezometric pressure data for existing spillway (Q=2909.8 ft^3/s)

Spillway discharge (ft^3/s) 2909.8	Tailwater El. (ft) 996.0	Reservoir El. (ft) 1054.1	Data filename DRUCK5.ASC	
Tap No.	X coordinate (ft)	Y coordinate (ft)	Piezometric elevation (ft)	Pressure head (ft H_2O)
1	0.00	1049.92	1055.76	5.84
2	0.63	1050.10	1055.35	5.25
3	3.41	1049.23	1051.37	2.14
4	5.59	1047.37	1049.58	2.21
5	7.25	1045.36	1047.39	2.03
6	9.08	1042.33	1044.55	2.22
7	9.25	1039.35	1041.23	1.87
8	11.59	1034.56	1036.34	1.78
9	12.34	1030.60	1031.80	1.20
10	13.05	1023.69	1027.05	3.36
11	13.37	1016.73	1020.36	3.63
12	13.50	1009.53	1011.98	2.45
13	15.01	996.27	1024.01	27.75
14	19.32	990.46	1025.88	35.41
15	25.83	986.32	1024.35	38.03
16	38.40	984.80	995.60	10.80
17	103.85	984.70	1002.46	17.76
18	169.30	984.30	1000.75	16.45
19	234.75	984.08	997.32	13.25
20	300.20	983.79	996.08	12.30
21	0.63	1050.18	1053.32	3.14
22	3.41	1049.42	1051.97	2.55
23	5.59	1047.44	1049.95	2.51
24	7.25	1045.45	1047.29	1.84
25	9.08	1042.20	1042.88	0.67
26	9.25	1039.20	1040.50	1.30
27	38.95	994.47	n/a	n/a
28	43.00	994.45	n/a	n/a
29	46.76	994.43	n/a	n/a

Table A.3. - Piezometric pressure data for existing spillway (Q=3197.9 ft^3/s)

Spillway discharge (ft^3/s) 3197.9	Tailwater El. (ft) 996.32	Reservoir El. (ft) 1054.38	Data filename DRUCK6.ASC	
Tap No.	X coordinate (ft)	Y coordinate (ft)	Piezometric elevation (ft)	Pressure head (ft H_2O)
1	0.00	1049.92	1055.90	5.98
2	0.63	1050.10	1055.50	5.40
3	3.41	1049.23	1051.33	2.10
4	5.59	1047.37	1049.68	2.31
5	7.25	1045.36	1047.37	2.01
6	9.08	1042.33	1044.51	2.19
7	9.25	1039.35	1041.20	1.85
8	11.59	1034.56	1036.34	1.78
9	12.34	1030.60	1033.58	2.99
10	13.05	1023.69	1028.92	5.23
11	13.37	1016.73	1024.66	7.93
12	13.50	1009.53	1018.94	9.41
13	15.01	996.27	1031.43	35.16
14	19.32	990.46	1032.13	41.66
15	25.83	986.32	1029.47	43.15
16	38.40	984.80	1009.81	25.02
17	103.85	984.70	1005.95	21.25
18	169.30	984.30	1003.29	19.00
19	234.75	984.08	999.28	15.21
20	300.20	983.79	997.17	13.39
21	0.63	1050.18	1053.24	3.06
22	3.41	1049.42	1051.94	2.52
23	5.59	1047.44	1049.93	2.49
24	7.25	1045.45	1047.22	1.78
25	9.08	1042.20	1042.76	0.56
26	9.25	1039.20	1040.55	1.35
27	38.95	994.47	n/a	n/a
28	43.00	994.45	n/a	n/a
29	46.76	994.43	n/a	n/a

Table A.4. - Piezometric pressure data for existing spillway (Q=3608.0 ft^3/s)

Spillway discharge (ft^3/s) 3608.0	Tailwater El. (ft) 996.73	Reservoir El. (ft) 1055.03	Data filename DRUCK7.ASC	
Tap No.	X coordinate (ft)	Y coordinate (ft)	Piezometric elevation (ft)	Pressure head (ft H_2O)
1	0.00	1049.92	1056.46	6.55
2	0.63	1050.10	1056.21	6.12
3	3.41	1049.23	1054.69	5.46
4	5.59	1047.37	1054.84	7.47
5	7.25	1045.36	1054.54	9.18
6	9.08	1042.33	1053.23	10.90
7	9.25	1039.35	1050.85	11.49
8	11.59	1034.56	1047.31	12.74
9	12.34	1030.60	1040.42	9.83
10	13.05	1023.69	1030.30	6.61
11	13.37	1016.73	1021.45	4.72
12	13.50	1009.53	1018.97	9.44
13	15.01	996.27	1034.81	38.54
14	19.32	990.46	1035.01	44.55
15	25.83	986.32	1034.40	48.08
16	38.40	984.80	1016.44	31.64
17	103.85	984.70	1007.58	22.88
18	169.30	984.30	1005.51	21.21
19	234.75	984.08	1000.75	16.68
20	300.20	983.79	997.67	13.88
21	0.63	1050.18	1054.59	4.41
22	3.41	1049.42	1054.79	5.37
23	5.59	1047.44	1055.15	7.71
24	7.25	1045.45	1054.69	9.25
25	9.08	1042.20	1052.97	10.77
26	9.25	1039.20	1051.15	11.95
27	38.95	994.47	n/a	n/a
28	43.00	994.45	n/a	n/a
29	46.76	994.43	n/a	n/a

Table A.5. - Piezometric pressure data for existing spillway (Q=3945.6 ft^3/s)

Spillway discharge (ft^3/s) 3945.6	Tailwater El. (ft) 997.04	Reservoir El. (ft) 1059.31	Data filename DRUCK8.ASC	
Tap No.	X Coordinate (ft)	Y Coordinate (ft)	Piezometric elevation (ft)	Pressure head (ft H_20)
1	0.00	1049.92	1060.38	10.46
2	0.63	1050.10	1060.30	10.20
3	3.41	1049.23	1059.63	10.40
4	5.59	1047.37	1059.72	12.35
5	7.25	1045.36	1059.40	14.05
6	9.08	1042.33	1057.81	15.48
7	9.25	1039.35	1054.90	15.55
8	11.59	1034.56	1050.61	16.05
9	12.34	1030.60	1043.07	12.48
10	13.05	1023.69	1032.59	8.89
11	13.37	1016.73	1023.13	6.40
12	13.50	1009.53	1020.35	10.82
13	15.01	996.27	1037.28	41.01
14	19.32	990.46	1037.52	47.06
15	25.83	986.32	1036.85	50.53
16	38.40	984.80	1017.38	32.58
17	103.85	984.70	1008.35	23.65
18	169.30	984.30	1006.50	22.20
19	234.75	984.08	1001.66	17.58
20	300.20	983.79	998.13	14.35
21	0.63	1050.18	1059.48	9.30
22	3.41	1049.42	1059.45	10.03
23	5.59	1047.44	1059.24	11.80
24	7.25	1045.45	1058.54	13.09
25	9.08	1042.20	1056.60	14.39
26	9.25	1039.20	1054.59	15.39
27	38.95	994.47	n/a	n/a
28	43.00	994.45	n/a	n/a
29	46.76	994.43	n/a	n/a

Table A.6. - Piezometric pressure data for existing spillway (Q=4100.0 ft³/s)

Spillway discharge (ft³/s) 4100.0	Tailwater El. (ft) 997.18	Reservoir El. (ft) 1070.6	Data filename DRUCK9.ASC	
Tap No.	X coordinate (ft)	Y coordinate (ft)	Piezometric elevation (ft)	Pressure head (ft H_2O)
1	0.00	1049.92	1071.44	21.52
2	0.63	1050.10	1071.27	21.17
3	3.41	1049.23	1070.43	21.20
4	5.59	1047.37	1071.08	23.71
5	7.25	1045.36	1070.48	25.12
6	9.08	1042.33	1068.24	25.91
7	9.25	1039.35	1064.83	25.47
8	11.59	1034.56	1059.92	25.36
9	12.34	1030.60	1050.91	20.32
10	13.05	1023.69	1038.55	14.86
11	13.37	1016.73	1027.52	10.79
12	13.50	1009.53	1024.97	15.44
13	15.01	996.27	1044.21	47.94
14	19.32	990.46	1044.72	54.25
15	25.83	986.32	1044.01	57.69
16	38.40	984.80	1021.60	36.81
17	103.85	984.70	1011.03	26.33
18	169.30	984.30	1008.60	24.30
19	234.75	984.08	1003.17	19.10
20	300.20	983.79	999.03	15.25
21	0.63	1050.18	1071.18	20.99
22	3.41	1049.42	1070.37	20.95
23	5.59	1047.44	1069.86	22.42
24	7.25	1045.45	1068.94	23.49
25	9.08	1042.20	1066.84	24.63
26	9.25	1039.20	1064.72	25.52
27	38.95	994.47	1018.95	24.48
28	43.00	994.45	1019.95	25.50
29	46.76	994.43	1019.69	25.26

Table A.7. - Piezometric pressure data for existing spillway (Q=4240.0 ft^3/s)

Spillway discharge (ft^3/s) 4240.0	Tailwater El. (ft) 997.3	Reservoir El. (ft) 1075.0	Data filename DRUCK10.ASC	
Tap No.	X coordinate (ft)	Y coordinate (ft)	Piezometric elevation (ft)	Pressure head (ft H_2O)
1	0.00	1049.92	1076.15	26.24
2	0.63	1050.10	1075.95	25.86
3	3.41	1049.23	1075.10	25.87
4	5.59	1047.37	1075.20	27.83
5	7.25	1045.36	1074.60	29.24
6	9.08	1042.33	1072.29	29.96
7	9.25	1039.35	1068.58	29.23
8	11.59	1034.56	1063.32	28.75
9	12.34	1030.60	1053.99	23.39
10	13.05	1023.69	1040.75	17.06
11	13.37	1016.73	1029.26	12.54
12	13.50	1009.53	1026.16	16.62
13	15.01	996.27	1046.72	50.45
14	19.32	990.46	1047.17	56.70
15	25.83	986.32	1046.16	59.84
16	38.40	984.80	1022.44	37.65
17	103.85	984.70	1011.66	26.96
18	169.30	984.30	1009.31	25.01
19	234.75	984.08	1003.04	18.96
20	300.20	983.79	999.43	15.64
21	0.63	1050.18	1075.35	25.17
22	3.41	1049.42	1075.10	25.68
23	5.59	1047.44	1074.70	27.26
24	7.25	1045.45	1073.80	28.35
25	9.08	1042.20	1071.39	29.19
26	9.25	1039.20	1068.83	29.63
27	38.95	994.47	1020.15	25.68
28	43.00	994.45	1021.04	26.59
29	46.76	994.43	1020.74	26.31

Table A.8. - Piezometric pressure data for spillway with recommended flow deflector and 0.7-ft diameter air vent (Q=2323.0 ft^3/s)

Spillway discharge (ft^3/s) 2323.0	Tailwater El. (ft) 995.2	Reservoir El. (ft) 1060.0	Data filename DEFL21.ASC	
Tap No.	X coordinate (ft)	Y coordinate (ft)	Piezometric elevation (ft)	Pressure head (ft H_2O)
1	0.00	1049.92	1061.23	11.31
2	0.63	1050.10	1061.18	11.09
3	3.41	1049.23	1060.96	11.73
4	5.59	1047.37	1061.00	13.63
5	7.25	1045.36	1060.92	15.56
6	9.08	1042.33	1060.35	18.02
7	9.25	1039.35	1059.37	20.02
8	11.59	1034.56	1057.77	23.21
9	12.34	1030.60	1055.23	24.63
10	13.05	1023.69	1051.53	27.83
11	13.37	1016.73	1048.32	31.59
12	13.50	1009.53	1047.18	37.64
13	15.01	996.27	1049.49	53.22
14	19.32	990.46	1036.99	46.52
15	25.83	986.32	1023.21	36.89
16	38.40	984.80	992.31	7.52
17	103.85	984.70	988.18	3.48
18	169.30	984.30	990.18	5.88
19	234.75	984.08	990.15	6.07
20	300.20	983.79	989.81	6.03
21	0.63	1050.18	1061.06	10.88
22	3.41	1049.42	1061.02	11.60
23	5.59	1047.44	1060.93	13.49
24	7.25	1045.45	1060.68	15.23
25	9.08	1042.20	1060.01	17.81
26	9.25	1039.20	1059.29	20.09
27	38.95	994.47	n/a	n/a
28	43.00	994.45	n/a	n/a
29	46.76	994.43	995.12	0.69
27A	23.50	998.57	1038.25	39.68
28A	28.00	994.87	995.20	0.33

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